Estimation of Snow Water Equivalent over the Fort Randall and Big Bend Watersheds, 1996-1997

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INTRODUCTION

This is the second effort between the Northwestern Division Missouri River Region office and the Cold Regions Research Engineering Lab (CRREL) on the operational monitoring of the snowpack of large Great Plains watersheds. Extensive snow cover on the Great Plains can have a significant impact on the operation of the Missouri River Mainstem Reservoir System operated by the Corps of Engineers (Corps). The six projects comprising the system include Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point. Extensive snow covers can represent large volumes of water distributed over the watershed that must be taken into account in the operation of the reservoirs. The current lack of reliable and timely operational snow monitoring of the snow cover throughout the Great Plains portion of the Missouri River watershed can potentially cause problems in the operation of the reservoir system. As an example, the 1997 April and May runoff was estimated at 10 million acre-feet. Fifteen million acre-feet of runoff actually occurred in that time period.

Operational snow monitoring in the Great Plains is difficult for two primary reasons. First, the plains snowpack exhibits great spatial and temporal heterogeneity due to episodic snowfall events, which vary widely from location to location and year-to-year, and subsequent redistribution of snow during windy periods. Second, the relatively low frequency of significant snow cover and the sparse population of many areas of the Great Plains result in few regular observations of the water held in the snow cover, and the spatial density of reporting weather stations is relatively low. This situation has led the Corps to send personnel into the field during winters of extensive snow cover to manually measure the snow cover depth and its properties. This effort proved to be time consuming and expensive, and it had an unknown accuracy.

The primary product of a snow monitoring system useful to Corps water control is a reliable and frequently updated map of the depth of the snow water equivalent (SWE) over the watersheds of interest. In this report, five approaches are investigated for estimating the SWE over the watersheds of the Fort Randall and Big Bend reservoirs. These approaches do not require that the Corps conduct field

measurements of any type and have the potential for operational use. They rely on existing data sources that are not being fully exploited by the Corps at this time to estimate SWE.

BACKGROUND

This study focused on the watersheds of the Fort Randall and Big Bend reservoirs during the winter of 1996-97 and assessed the reliability of five approaches for estimating the total snow water volume over the watershed. The approaches differed in the processes followed to estimate the total water volume of the snowpack in each sub-watershed but were similar in the following respects. Each approach established a 1-km × 1-km grid over the watersheds of Fort Randall and Big Bend reservoirs. The snow properties of depth or SWE required for each approach was determined for each grid cell on each day. The approaches varied in the method used to estimate the snow property for each grid cell, but generally an inverse distance weighted (IDW) algorithm was used to interpolate point estimates. Each of the approaches also required an independent estimate of snow-covered area (SCA). Recently developed algorithms were used to map snow at sub-pixel resolution from the (NOAA) Advanced Very High-Resolution Radiometer (AVHRR) (Rosenthal and Dozier 1996). Estimates of SCA were expressed as fractional cover per grid cell. Also, an empirical relationship between the mean snow depth and the mean SCA for all of the watersheds of the Fort Randall, and Big Bend reservoirs was used in one approach.

In brief, the five approaches are

- 1. **Modeled SWE.** In this approach the SSARR_grid snow process model was used to estimate SWE. SSARR_grid estimates SWE at a point based on the temperature index, melt-factor approach. It can be considered a procedure to "synthesize" SWE at a location from observed meteorological observations. Only the air temperature and precipitation are required at any specific location. Once the SWE was estimated at each NWS station, the SWE for each grid cell was found using IDW. This SWE was then multiplied by the SCA of that grid cell and the cell area to arrive at the volume of water contained in that cell. The volume of water in each cell in each sub-watershed were then summed to arrive at the total volume of water contained in the snow cover in each watershed.
- 2. **NWS Snow Depth.** The National Weather Service (NWS) has many stations located throughout the Great Plains. Only snow depth is reported at most of the measurement locations (third-order stations). To convert to SWE, the snow density must be estimated. Monthly snow density was estimated based on all of the NWS and Corps measurement of snow density made in 1997. This density was then multiplied times the snow depth to estimate SWE. Once the SWE at each NWS station was determined, this approach is identical to the Modeled SWE approach described above. Next, the SWE for each grid cell was found using IDW. This SWE was then multiplied by the SCA of that grid cell and the cell area to arrive at the volume of water contained in that cell. The volume of water for

- each of the cells in each sub-watershed was then summed to arrive at the total volume of water contained in the snow cover in each watershed.
- 3. **SSM/I.** The Special Sensor Microwave/Imager (SSM/I), one of several sensors carried on Defense Meteorological Satellite Program (DMSP) satellites, measures passive microwave radiation, which is microwave radiation emitted by the Earth. The passive microwave measurements can be converted to SWE using the algorithm of Goodison and Walker (1994). The SSM/I estimates SWE in cells approximately 25 km on a side. These estimates were then transferred to the 1-km grid cells by assigning each 1-km grid cell the value of its SSM/I closest neighbor. This SWE was then multiplied by the SCA of that 1-km grid cell and the cell area to arrive at the volume of water contained in that cell. The volume of water contained in the snow cover in each watershed.
- 4. **NWS Measured Snow Depth Biased with SSM/I.** In this approach the SWE at each NWS station was estimated using the measured snow depth and the estimated monthly snow density, as in approach 2 described above. The SWE in each grid cell was also estimated using the SSM/I data as described in approach 3 above. In this case, however, the SSM/I SWE value for each 1-km grid cell was used as a "bias" surface to aid in the interpolation of the point measurements. In short, the interpolation procedure interpolates only that fraction of the point measurement that is not described by the SSM/I SWE estimate to arrive at an estimate of the SWE in each grid cell. This SWE was then multiplied by the SCA of that grid cell and the cell area to arrive at the volume of water contained in that cell. The cells in each sub-watershed were then summed to arrive at the total volume of water contained in the snow cover in each watershed. The advantage of this approach is that it combines the NWS field measurements with the SSM/I data.
- 5. **NWS Measured Snow Depth with Empirical SCA.** This approach requires only the snow depths measured at the NWS stations. These measurements are used to estimate the snow depth in each 1-km grid cell using IDW. The mean depth of each sub-watershed is then found based on the grid cells it contains. CRREL also developed an empirical relationship between the mean snow depth and the mean SCA for all the watersheds of the Oahe, Fort Randall, and Big Bend reservoirs. This relationship was found by fitting a non-linear curve to the measurements of SCA based on the NOAA AVHRR and the mean depth of snow in the watershed based on the NWS observations. The SWE of each sub-watershed is estimated by multiplying the mean snow depth by the appropriate monthly snow density and the empirical estimate of SCA based on the snow depth.

Study Area

The Fort Randall Dam is located at Pickstown, SD. The reservoir extends over 107 miles upstream toward the Big Bend Dam at Fort Thomas, SD. The

reservoir of Big Bend Dam is about 80 miles long and extends back to the base of the Oahe Dam. The study area was divided into twelve sub-basins that contribute to the Missouri River within the study area, of which seven had operational gages at their outlets during the winter of 1996-97. The sub-basins are shown in Figure 1. The watershed is approximately 1340 square miles in area for Fort Randall and 530 square miles in area for Big Bend, and almost entirely within South Dakota. The westernmost tip of the study area dips south into Nebraska. The mean wintertime precipitation (Dec-Feb) is about 1.5 inches over the watershed. The mean temperature for January is between 19° and 20°F, with extreme cold temperatures of –10°F to – 25°F.

Congress authorized the Fort Randall Dam and Big Bend Dam for the development of water resources within the Missouri River Basin. The hydroelectric power that they generate supplies electricity to meet the needs of 245,000 homes. In addition to flood control and power generation, these projects provides navigation support, irrigation, municipal water supply, recreation, and fish and wildlife enhancement. The Big Bend hydroelectric power plant is operated to meet peak demands for electricity in the Missouri River Basin.

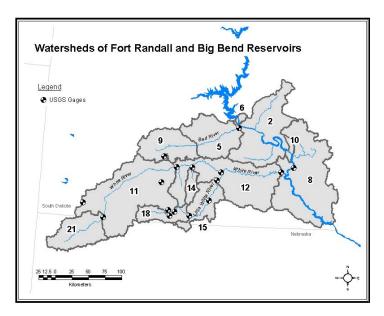


Figure 1. Watersheds of Fort Randall and Big Bend reservoirs.

RESULTS

Each approach required estimates of SWE and SCA. The frequency at which the SWE and SCA estimates are available controls the number of estimates that could be provided over the season. There are three independent means of estimating SWE over the watersheds: NWS point measurements of snow depth combined with historical measurements of monthly snow density; analysis of microwave radiation measured by the SSM/I converted to SWE using the algorithm of Goodison and Walker (1994); and modeled SWE using a temperature index snow model,

SSARR grid, applied at discrete points. All three of these means of estimating SWE could potentially provide daily estimates of SWE. The SSM/I Goodison and Walker (1994) algorithm has difficulty with wet snow, which reduced the number of days of data. There is only one means of estimating SCA: the AVHRR imagery. Also developed was an empirical estimate of SCA based on the AVHRR results and the recorded snow depths. The AVHRR imagery is only available on days when clouds do not obscure the ground surface. During the winter of 1996-97, the AVHRR imagery was available on 30 dates, or 18.75% of the days. This is approximately 1 day every 5 or 6 days, which is sufficient for operational use. The empirical estimation of SCA could be used on every day in which a snow depth estimate could be made, which is 100% of the winter season. The four methods that use the AVHRR estimate of SCA were limited to 30 days over the winter season. The SSM/I estimate of SWE was not available for all of the days when the AVHRR imagery was available. The presence of wet snow and lack of coverage of the watersheds of the Fort Randall and Big Bend reservoirs further limited the SSM/I data to 8.5% of the days of winter. This is less than 1 day in 10, but may be sufficient for operational use. The SSM/I results were developed as a research project only. During operational use, it may be possible to increase the number of days that the SSM/I data are available.

It would be ideal to compare the results of each approach to actual field measurements. Unfortunately direct measurements were not made of the SWE over these watersheds during the winter of 1996-97. In lieu of comparing the results to the actual field conditions, the consistency of the results and the volume of SWE estimated over the watersheds were compared to the volume of runoff measured at the outflow of the major watersheds, and the generated SWE maps were reviewed.

Total SWE

The mean SWE over the entire watershed of the Fort Randall and Big Bend reservoirs estimated by each of the five approaches for the entire winter season is shown in Figure 2. The red bars are the means based on all the days estimated over the entire winter season. The blue bars are means based only on the days when the SCA data and SSM/I data were both available. The blue bars provide a direct comparison of the different approaches. All the approaches except the modeled SWE are within 8.0% of the mean of the four approaches when compared directly. The means based on all the data display a greater spread. First of all, NWS with empirical SCA could be applied for the most days over the winter season. Many of the days that were not estimated by the other approaches were days with relatively low SWE over the watershed. Including these days in the overall mean for NWS with empirical SCA lowered its mean. If only the days when all approaches had data are included, this approach produces the maximum estimate of SWE. NWS measured snow depth and Modeled SWE were available on every day on which the AVHRR imagery was available. Again, many of the days not estimated by SSM/I and NWS-SSM/I were relatively low days. Including these days in the overall mean for NWS measured snow depth and Modeled SWE tends to lower their mean. This cannot entirely explain the relatively low overall mean provided by the *Modeled SWE* approach. The *Modeled*

SWE is consistently low, both in the direct comparison and based on all the days of data. Recall that the SSARR_grid model uses measurements of the air temperature and precipitation to estimate SWE directly. It is likely that systematic undercatch of precipitation by the NWS rain gages due to wind is the cause of this low SWE estimate.

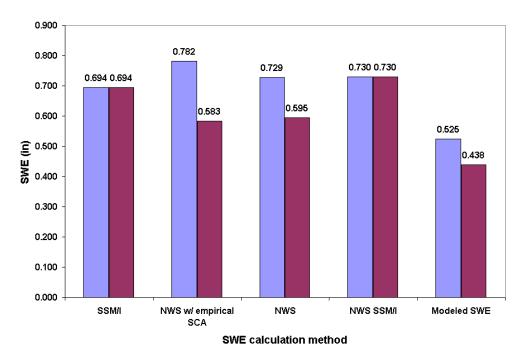


Figure 2. Mean SWE for the 1996-97 winter for the entire watershed. (Red - entire winter season; blue - dates only when AVHRR and SSM/I data were available.)

Direct Comparison of SWE Estimation

Direct comparisons of the SWE estimated by each approach shows that the Modeled SWE produced significantly lower estimates and that the Modeled SWE increasingly underestimated the SWE as the SWE increased. This is the result of the systematic undercatch of the precipitation gages in the basins because of wind. The four remaining approaches produce results that are more or less consistent. While there is some scatter, there is not a consistent bias in the results.

The snow-covered area was estimated based on the AVHRR imagery using the method of Rosenthal (1996). This method provides a direct and independent means of estimating the SCA. An empirical "model" was developed of the SCA based on the mean snow depth in each watershed. The parameters were estimated by fitting the model to the SCA determined from the AVHRR imagery and the snow depths reported by the NWS for the same day. In Figure 3, the histograms of the results of each method of estimating SCA are compared. The empirical model tends to estimate SCA values in the range 0.5–1.0 more often than the AVHRR imagery, and values in the range of 0.1–0.5 less often. This may account for the generally

larger SWE values that are estimated by the *NWS with empirical SCA* approach then the other approaches when compared directly. The empirical model can produce a maximum SCA of approximately 0.94. The AVHRR imagery SCA can reach a maximum of approximately 0.98 when the watershed is 100% snow-covered. The result of these differing maxima can be seen in Figure 3.

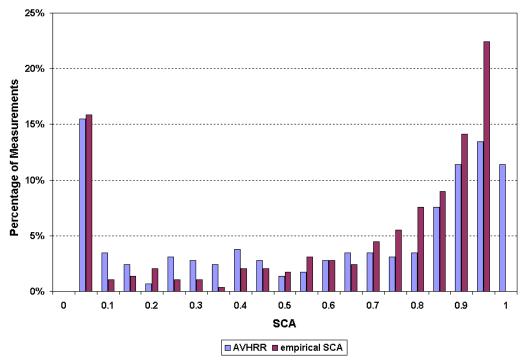


Figure 3. Histogram of the AVHRR SCA and the empirical estimate of SCA.

Comparison of SWE with the Measured Runoff Volume

While there can be a direct relationship between the volume of SWE in a watershed and the volume of runoff from that watershed during a period of snowmelt, one cannot expect all of the snow to be converted to channel flow. Starting with the snow on the ground, there are a number of alternative paths for that snow besides ending up as flow in a channel. The snow can evaporate directly into the air through sublimation. The fate of snowmelt that drains to the base of the snowpack depends on the slope, snow, and soil conditions. Snowmelt behaves much as rainfall and can result in stream flow or the recharge of deep aquifers. Overland flow may evaporate or become "trapped" in shallow depressions and not enter stream channels. Once in the stream channels, the flow may be impeded by the presence of river ice, especially if ice jams form. This can cause flooding of upland areas, resulting in the formation of wetland areas and the stranding of ice in the stream overbank area, with both reducing the volume of stream flow.

There are two major sub-watersheds that were analyzed for runoff: the Bad River, with a downstream gage at Fort Pierre, SD, and the White River, with a downstream gage at Oacoma, SD. The Bad River watershed comprises watersheds 5

and 9. The White River watershed comprises watersheds 21, 11, 18, 14, 15, and 12. Comparisons are made with the volume of runoff over the period of snowmelt to the volume of SWE over the watershed at the beginning of the melt period to assess the reasonableness of the SWE estimation. First the period of snowmelt must be defined. The total SWE and the discharge from each watershed are shown in Figures 4 and 5 for the Bad and White Rivers, respectively. Each runoff event is numbered under the discharge hydrographs. There were three runoff events for the Bad River and two for the White River. In Table 1, the volume of runoff for each sub-basin during the major snowmelt period is expressed as a depth in inches over the sub-basin. The volume of SWE in each sub-basin was estimated on the dates that are circled in Figures 4 and 5 and are also shown in Table 1. The volume of SWE that melted was estimated by the difference between the maximum closest to the circled date and the next minimum. Table 2 lists the ratios of the runoff to the volume of SWE. In general, the ratio of runoff to the volume of SWE ranges from 0.10 to greater than 1.0, depending on the method used to estimate SWE. (The events with a ratio greater than one are highlighted with yellow in the table.) Values greater than one suggest that either some of the SWE was not accounted for or that rain occurred during the melt period. The Modeled SWE approach produced ratios of greater than one for three out of the six events. This is consistent with the generally lower estimated SWE produced by the model. The NWS with empirical SCA and NWS-SSMI each produced only one ratio greater than one. The remaining two approaches each produced two ratios greater than one. These ratios were reasonable, given the likely losses of snow to evaporation, deep infiltration, interception, etc.

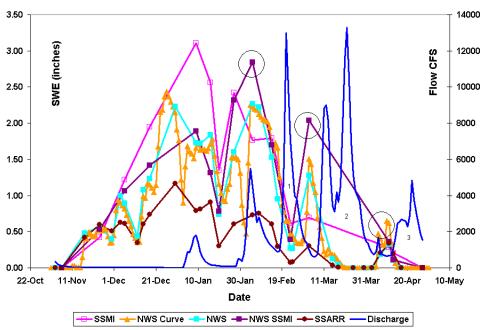


Figure 4. SWE and measured flow of the Bad River near Fort Pierre, SD.

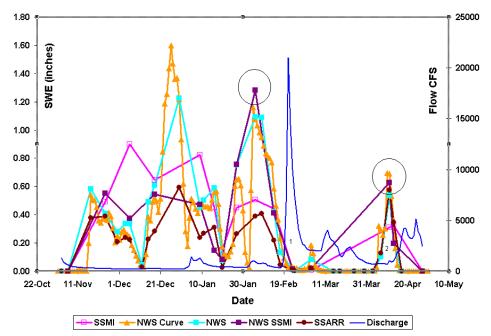


Figure 5. SWE and measured flow of the White River near Oacoma, SD.

Table 1. Observed runoff events and SWE calculations.

	Runoff Events			SWE calculation comparison				
			Average		NWS		NWS	
	Start	End	Runoff		Snow	NWS	empirical	Modeled
Watershed	Date	Date	Depth (in)	SSM/I	Depth	SSM/I	SCA	SWE
5	18-Feb	2-Mar	0.762	1.810	2.004	2.450	1.909	0.674
	8-Mar	31-Mar	1.647	0.695	1.280	2.036	1.509	0.306
	13-Apr	30-Apr	0.481	0.277	0.323	0.364	0.619	0.339
12	18-Feb	28-Feb	0.278	0.506	1.093	1.282	1.162	0.408
	13-Apr	30-Apr	0.167	0.311	0.539	0.626	0.693	0.574

Table 2. Ratio of observed runoff events to SWE calculations.

	Runoff Events			Runoff/SWE Calculations				
			Average		NWS		NWS	
	Start	End	Runoff		Snow	NWS	empirical	Modeled
Watershed	Date	Date	Depth (in)	SSM/I	Depth	SSM/I	SCA	SWE
5	18-Feb	2-Mar	0.762	0.421	0.380	0.311	0.399	1.130
	8-Mar	31-Mar	1.647	2.368	1.287	0.809	1.092	5.389
	13-Apr	30-Apr	0.481	1.736	1.489	1.322	0.778	1.422
12	18-Feb	28-Feb	0.278	0.549	0.254	0.217	0.239	0.680
	13-Apr	30-Apr	0.167	0.538	0.310	0.267	0.241	0.291

SWE Maps

The mean SWE distribution across the entire watershed is shown in Figure 6 for the *NWS measured snow depth*, *NWS-SSM/I*, *SSM/I*, and *Modeled SWE*. Each of

these approaches used the SCA estimate from the AVHRR imagery. (The approach *NWS with empirical SCA* can only produce estimates on a watershed scale and is not shown.) The maps are similar in overall layout, with the greatest depth of SWE in the northeast portion of the watershed and the least in the western regions. The presence of the relatively large grid cells produced by the SSM/I estimates of SWE can be discerned in the maps of *NWS-SSM/I* and *SSM/I*, although they are less pronounced in the *NWS-SSM/I*.

SUMMARY

This study mapped snow cover extent during the 1996-97 water year using multispectral measurements from the operational NOAA sensor AVHRR. By estimating snow extent as fractional coverage on a pixel-by-pixel basis, the extent maps provided information on the amount of snow-free area. Significant portions of the watersheds of the Fort Randall and Big Bend reservoirs have open landscape, ideal for observing snow cover, when cloud cover permitted. Also developed was an empirical model of SCA based on mean snow depth. The SWE sources were merged with the SCA estimate produced through the AVHRR imagery to construct periodic maps of water equivalent on each of the watersheds. Also merged, was the NWS snow depth estimates with the empirical SCA estimate to arrive at a daily subwatershed-by-sub-watershed estimate.

Each method produced roughly similar results except for the *Modeled SWE* results, which were consistently low. Systematic undercatch of precipitation during snowfall caused by wind is the likely explanation of the relatively low estimates produced by this method.

The results produced by the NWS snow depths combined with historical snow density estimates and merged with empirical SCA estimates were consistent with the other approaches though slightly higher. This approach offers the advantage that estimates can be made on a daily basis, without reference to the cloud cover over the watershed throughout the winter season using only the reported snow depths at NWS gage sites.

It is believed that SSM/I data have potential for enhancing operational snow mapping techniques. While the spatial resolution is coarse, they are available almost daily, have the capability for estimating SWE as well as SCA under dry snow conditions, and are independent of cloud cover.

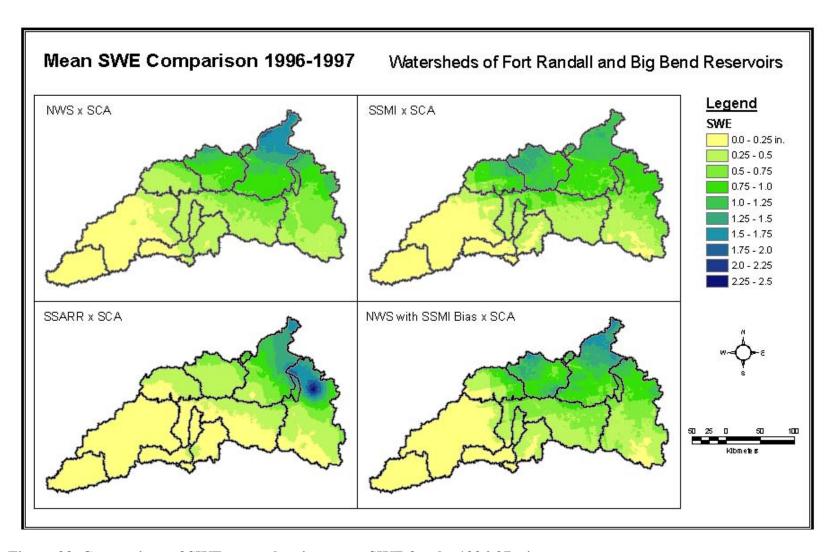


Figure 23. Comparison of SWE maps showing mean SWE for the 1996-97 winter.

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